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Energy retrofit of a historic building using simplified dynamic energy modeling

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Abstract

Energy retro-commissioning of historical buildings is an important challenge that implies both historic-artistic and technological aspects concerning the improvement in energy efficiency and comfort. A critical analysis of each possibility is essential in order to preserve the balance between efficiency and architecture. The research focuses on a historical building owned by ANCE (Associazione Nazionale Costruttori Edili), situated in Rome in the Nomentano district. Retrofitting hypothesis were made in order to improve HVAC systems, building’s envelope and building’s management, always respecting its architectural features. An energy audit has been done in order to evaluate the possibilities. The first step of the study consisted of a measure campaign conducted by Avvenia to know more about the actual use of the building. Next, a dynamic simplified energy modeling of the building has been built using the software ArchiEnergy. This allowed to preview the effect of modifications on the HVAC and envelope systems. Although starting from an original medium energy performance, simulations showed that it would be possible to reach a further reduction of energy needs by making simple changes in the management/controls domain and, with higher costs, by upgrading envelope components. This study shows that a correct approach can lead to both relevant energetic results and the conservation of architectural characteristics of historical buildings.

Keywords: energy retrofit, energy saving, public housing, existing buildings, energy audit, retrofit, dynamic simulation, ArchiEnergy.

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1. Building characteristics

The target of this study (Fig.1) is a building located in Rome in the Nomentano district and is part of an early ‘900 urban expansion zone [2] previewed by the City Plan of 1909, characterized by the present of isolated buildings surrounding the city walls and inspired by the concept of the “garden city”.

The building is a block composed of 5 floors over earth; the gross area of each floor is about 370 m^2, and the net area is about 240 m^2; the internal spaces are characterized by high inter-floor heights of about 3,50 m, with false ceiling in some case.

a b

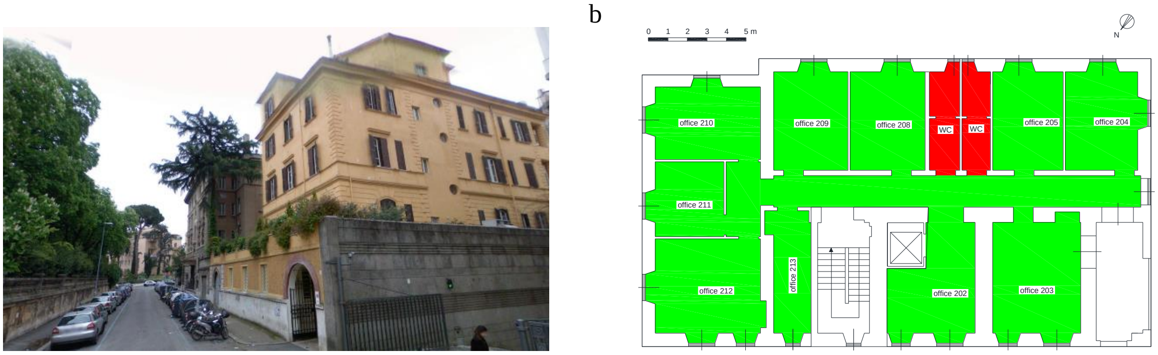

Fig.1. (a) View of the building. (b) 2° floor map. Green zones are heated/cooled, red zones are heated only.

Envelope characteristics have been determined by a historical study and by non-destructive assay (NDA). Vertical load-bearing walls are massive, built with 3-4 layers of bricks and resulting in a total thickness ranging from 45 cm (high floors) to 89 cm (low floors). This leads to a mass ranging from 656 to 1360 kg/m^2 and a high thermal inertia. The thermal transmittance of vertical walls varies from 0.60 to 1.08 W/m^{2}K. Horizontal structures are of two types: bricks pavilion vaulted slabs at ground floor and mixed bricks and metal profiles vaulted slabs on the other floors. This is a typical solution for roman high value buildings of early ‘900. The mass of horizontal structures is about 550 kg/m^2 and the thermal transmittance is about 1.1 W/m^{2}K. Glazed elements consist of old wooden windows with single glazing. The thermal transmittances are about 5.75 W/m^{2}K for glasses and about 2.39 W/m^{2}K for frames. Thus resulting in a total thermal transmittance of the windows ranging from 3.70 to 4.54 W/m^{2}K depending on the dimensions.

A thermographic analysis has been done with equipment FLIR mod. T365 (Fig.2). The aims of the analysis were: to validate the historical study about envelope components, to improve the thermal model of the building, to highlight thermal bridges. The thermographic assessment showed that:

- walls are compact and uniform everywhere in the building; the influence of thermal bridges is low; the thermal resistance of walls is generally low, especially under the windows;
- slabs have thermal bridges in the connections with walls due to the presence of metal profiles;
- wooden windows have high air leakages; the thermographic analysis revealed a surface temperature of the glasses of about 14°C with an external temperature of 12°C;
- the surface temperature of radiators is 60°C; in these conditions, with an external temperature of 10°C, the temperature of the toilets is about 20-21°C.

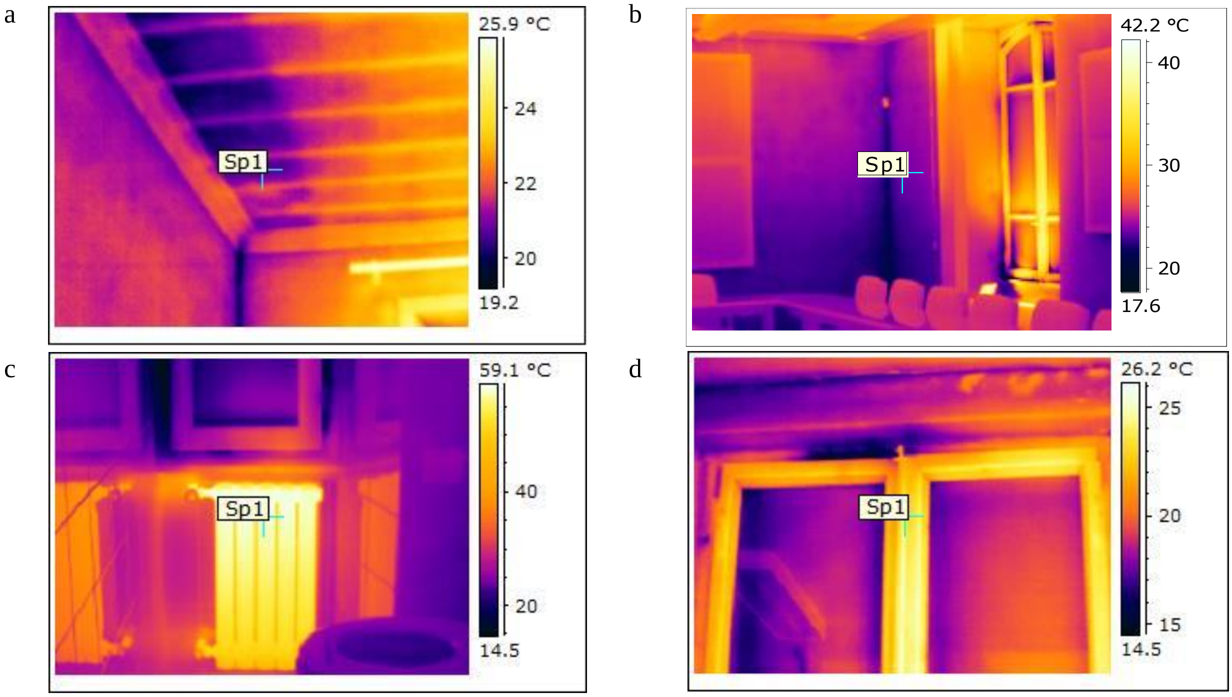

Fig. 2. (a) Mixed bricks and metal profiles vaulted slabs without insulation. (b) Vertical bricks load-bearing walls without insulation and single glazing windows. (c) High temperature of radiators in the toilets, weak insulation under the windows. (d) High thermal transmittance of the single glazing windows and high air leakages.

Each floor has an independent HVAC system, except for the toilets that have a common heating system. The HVAC system in the offices is composed by air-to-air direct expansion internal units, connected to an unique external unit for each floor. This results in five electric heat pumps, one for each floor, with a total power of 126kW for cooling (EER 4.29) and 140 kW for heating (COP 4.5).

The toilets are provided with a heating system composed by radiators connected to a central natural gas boiler. The boiler is located in the thermal power station over the roof and has a nominal thermal power of 170kW with an efficiency of 86.9% at 30% of load and 90.4% at 100% of load. Originally the heater was designed to serve the entire building but currently, after the installation of heat pumps, it serves only the toilets of all floors.

2. Temperatures and electric consumption monitoring

For eight months, from February to October, external and internal air temperatures and heat pumps electric energy consumption have been monitored hourly by Avvenia. For temperature measurements two A class PT100 thermo-resistances have been used, one positioned externally and one internally in one sample room. For energy measurements a watt-meter has been used, positioned on the electric input of heat pumps. Data-logging has been done using a PLC (Programmable Logic Controller). Measures and comparisons with simulated values are reported in Fig. 3a for the winter period (February-March) and in Fig.3b for the summer period (July-August). Due to logistic reasons it hasn't been possible to monitor the central part of the winter.

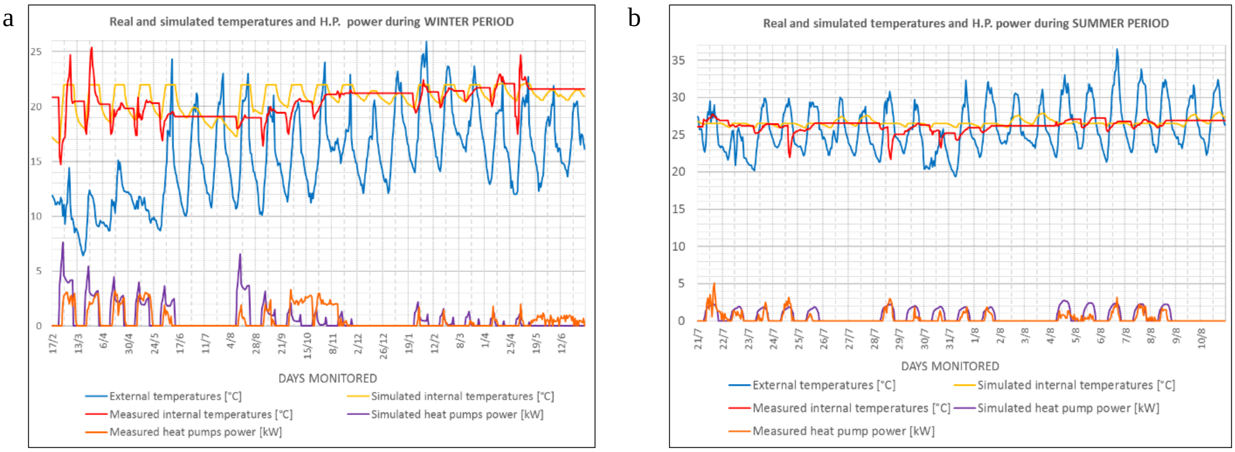

Fig. 3. (a) Internal and external temperatures and 2nd floor heat pump electric power monitoring and simulation. Period between February 17th and March 9th. (b) Internal and external temperatures and 2nd floor heat pump electric power monitoring and simulation. Period between July 21th and August 10th.

Fig. 3a shows that the internal temperature is quite stable during the winter period, despite of external wide temperature oscillations. This is a consequence of the high thermal capacity of the building. The internal temperature is about 22°C, close to the higher bound of the Italian law limits (20°C ± 2°C, DPR 412/93). Moreover it's possible to notice a sudden internal temperature reduction on the first working hours (up to 15-18°C), followed by a slow temperature raising to reach very high temperatures on the afternoon (up to 23-26°C). Comfort temperature is reached on average at about 13. The temperature reduction is due to the spaces cleaning operations. The temperature raising is too slow to reach a stable comfort temperature but, on the other side, the heat pumps are not used to their maximum power thus meaning that the internal units are too small. Temperature peaks are due to the thermal capacitance of the building and to the fact that users can select the set-point temperature without limitations.

During the summer (Fig. 3b) internal temperatures are highly stable in the surroundings of 26°C, with a maximum difference of 2°C between day and night, having an external temperature ranging from 20 to 33°C. Heat pumps are less used in summer than in winter, this fits with the lower summer thermal load resulting from simulations.

About HVAC controls, it has been observed that sometimes internal units are left ON also during non-working periods, this is a result of the lack of a central control system.

3. Simplified dynamic simulation and comparison with measured data

Current Italian laws about energy performance of buildings [3] are mainly based on the static monthly calculations of the UNI/TS 11300 standard (national application of the UNI EN ISO 13790), but they also suggest the use of more detailed dynamic simulations. Dynamic simulations, however, need high level modeling skills and longer time to complete. With the aim of creating a simpler but still accurate tool, the software ArchiEnergy has been implemented [4][5][6][7]. It allows to run hourly single-zone dynamic simulations and to execute economical calculations also including current financial incentives.

Simulations input data have been taken from building and plants inspection, measurement campaign, and from users and operators interviews. Hourly monitored temperatures and electrical absorptions have been used to fine-tune the simulation, particularly:

- to determine the exact external temperatures and internal set-points;
- to evaluate building's thermal inertia;
- to validate output data from simulations about electrical needs.

The first simulation step was to describe the current building. Once created, the model has been fine-tuned using measured data and validated by comparison with real yearly energy data (Table 1) and the difference is on average less than 1%.

Table 1. Comparison between real and simulated energy consumptions (fine-tuned using measured data).

	Yearly consumptions (real)	Yearly consumptions (simulated)	Difference
Natural gas [Sm^3]	5’300	5’560	4.9%
Electric energy [kWh]	81’000	81’425	0.5%

A second validation has been executed by comparison with real electric consumptions monitored on the heat pumps. Fig.4 shows that there is a strong correspondence between real and simulated data in a monthly scale too, with an average error of about 3%. Highest errors are reported during spring and autumn, when the energy balance is almost zero and so also small divergences begin to be relevant.

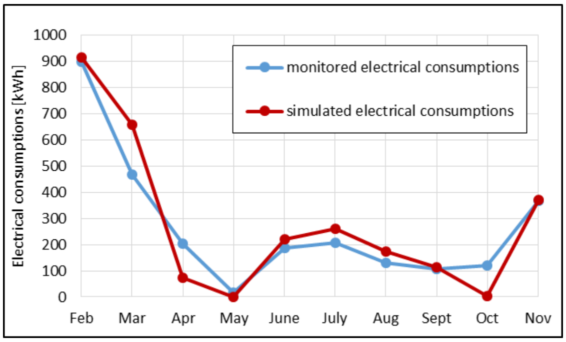

Fig.4: Comparison between 2nd floor heat pump monitored and simulated electrical consumptions.

A third validation has been done also on an hourly scale. Results (Fig.3a and Fig.3b) report a high correlation between monitored and simulated data, especially during the summer. In Table 2 are reported simulation results.

Table 2. Current simulated energy needs.

	Electric energy [kWh/y]	Thermal energy [kWh/y]
Heating	19.875	52.345
Cooling	3.840	
Lighting	21.100	
Other uses	36.600	
TOTAL	81.415	52.345

Carbon dioxide emissions associated to simulated energy needs are equal to 45.5 t/year and energy costs are equal to 23’260 euro/year. Renewable energy share is 33% thanks to the heat pumps. A detailed view of HVAC energy needs is reported in Table 3, where the area served by heat pumps (Zone 1 - Offices) and the area served only by radiators (Zone 2 - Toilets) have been separated.

Table 3. Useful and primary energy for HVAC.

	Useful energy [kWh]	Primary energy [kWh]	Seasonal mean efficiency
Heating (Zone 1)	65’975	43’208	1.53
Heating (Zone 2)	16’495	52’345	0.32
Heating (Total)	82’470	95’553	0.86
Cooling (Zone 1)	13’200	8’348	1.58

Useful energy use is 60.2 kWh/(m^2y) for heating and 9.6 kWh/(m^2y) for cooling. About heating, the building's useful energy need is similar to the average of the same age buildings in Rome (63.5 kWh/(m^2y), and slightly higher than the average of Rome's buildings (57.1 kWh/(m^2y) [8][9][10]. About cooling the building has a quite high performance. HVAC systems are characterized by a high seasonal efficiency (Table 3) with the exception of the toilets heating system which suffer of a very low efficiency (32%). Specific primary energy need for HVAC is 75.8 kWh/m^2y.

4. Retro-commissioning interventions simulations

The analysis showed that there are high possibilities to improve building's energy performance, mainly about building management, HVAC controls and envelope quality. Interventions are divided in two categories: short-term interventions (simple works without interruption of building's activities) and medium-term interventions (bigger works that need to stop building's activities). In the first category are: improving HVAC controls, turning off toilets heating, substituting windows. In the second category are: roof insulation, floor insulation, walls insulation.

4.1. Short-term interventions

The measurement campaign showed that during the cleaning operations in the morning, windows are left open with HVAC on, causing energy waste and reducing users comfort. A simple but effective intervention may be to move the cleaning operations in the evening, when the HVAC systems are off. This may lead to energy savings and to comfort improvement due to a better thermal comfort and air quality (there would be less dust and chemical substances in the air during working time). Other effective management interventions may be: limit winter temperature set-point to the Italian laws limit of 20° (less than the current average of 22°C) and centrally turn off the internal HVAC units during night-time and weekends by installing a central automatic control. The cost of these interventions are very limited (about 5'000 euro), because they don't need big structural works. These could lead to a money saving of 2'375 euro/year, with a payback time less than 2 years and a 10 years NAV of 15'000 euro.

Another very important solution is about the toilets heating system. This is done by a 170kW natural gas boiler that is currently feeding only 10 radiators, for a total thermal need of about 5kW. The high difference between nominal power and actual needed power leads to a very low efficiency of the heater. On the same time the heat pumps are used less than their nominal power, so it's possible to completely decommission the natural gas heater and assure toilets heating by the installation of extractor fans in order to take air from the corridors. The extractor fans will work continuously during the heating season working hours. This will lead to a higher air intake of 50 m^3/h for each toilet. The higher ventilation energy needs and the power consumption of the fans (14 W each) have been taken into account in the simulation. The cost of these interventions is practically zero. In fact the cost for the heater decommissioning and the installations of fans is about 5'000 euro but it's shortly compensated by the economic savings linked to the end of the maintenance of the heater and the end of the fixed costs of natural gas supply. Economic savings are estimated in about 3'690 euro/year; the payback time is immediate due to the zero costs; the 10 years NAV is about 30'000 euro.

The last short-term intervention is about glazed elements. The current windows are the weakest part of the envelope: they have a very high thermal transmittance (due to single glazing) and a very high air leakages. A substitution of the old windows is proposed with new ones having a thermal transmittance of 2.6 W/m^2K. The cost is about 86'500 euro without considering the tax deduction of 65%. The economical savings are about 6'985 euro/year, with a payback time of 15 years and a 10 years NAV of -9'000 euro. This shows that changing windows is a poorly convenient intervention.

The realization of all short-term interventions leads to a high energy performance improvement (Table 4), with a reduction of primary energy needs of 71.0% for heating and 18.4% for cooling. The primary energy need for HVAC changes from 75.8 kWh/m^2year to 25.3 kWh/m^2year, with a reduction of 66.7%. The renewable energy share changes from 33.0% to 31.2%.

Table 4. HVAC useful and primary energy needs for short-term interventions.

		Useful energy [kWh]	Useful energy variations [%]	Primary energy [kWh]	Primary energy variations [kWh]	Mean seasonal efficiency	Mean seasonal efficiency variations
Thermal controls	Heating	61’075	-25.9%	71’158	-25.5%	0.86	-0.6%
	Cooling	12’820	-2.9%	8’109	-2.9%	1.58	0.0%
Toilets heater decommissioning	Heating	82’550	0.1%	52’415	-45.1%	1.57	82.5%
	Cooling	13’200	0.0%	8’348	0.0%	1.58	0.0%
Windows change	Heating	59’055	-28.4%	68’151	-28.7%	0.87	0.4%
	Cooling	11’075	-16.1%	6’979	-16.4%	1.59	0.4%
All of above	Heating	43’110	-47.7%	27’751	-71.0%	1.55	80.0%
	Cooling	10’820	-18.0%	6’815	-18.4%	1.59	0.4%

Carbon dioxide emissions change from 45.5 t/year to 32.0 t/year with a reduction of 30.4 %. Economic savings are 10’615 euro/year. The total investment is about 89’000 euro, the payback time is 7.9 years, with a 10 years NAV higher than 16’500 euro. Thus short-term interventions have an excellent economic and environmental return.

4.2. Medium-term interventions

The present use of the building doesn’t allow retro-commissioning interventions that need a long interruption of working activities, such as envelope insulation. For this reason these are to be considered only in a medium-term view. The insulation has been considered to be placed on the inner part of envelope because the historical characteristics of the buildings doesn’t allow external modifications. The insulation has been designed to lead to a total thermal transmittance of envelope elements that is lower than law limits about economic incentives (tax deduction of 65%). Post-operam thermal transmittance values are: 0.29 W/m^{2}K for vertical walls, 0.26 W/m^{2}K for ceilings, 0.34 W/m^{2}K for floors over ground or over unconditioned spaces. The effect of these interventions is generally positive, leading to a better envelope winter performance, with a little worsening of summer performance (Table 5). The total cost of medium-term interventions can be estimated in 80’000 euro (without considering 65% tax deduction) and they may lead to an economic saving of 2’500 euro/year but with a payback time higher than 30 years.

Table 5. HVAC useful and primary energy needs for medium-term interventions.

		Useful energy [kWh]	Useful energy variations [%]	Primary energy [kWh]	Primary energy variations [kWh]	Mean seasonal efficiency	Mean seasonal efficiency variations
Vertical walls insulation	Heating	65’390	-20.7%	76’154	-20.3%	0.86	-0.5%
	Cooling	14’370	8.9%	9’098	9.0%	1.58	-0.1%
Ceiling insulation	Heating	74’765	-9.3%	86’815	-9.1%	0.86	-0.2%
	Cooling	13’720	3.9%	8’685	4.0%	1.58	-0.1%
Floor insulation	Heating	76’540	-7.2%	88’810	-7.1%	0.86	-0.1%
	Cooling	13’600	3.0%	8’609	3.1%	1.58	-0.1%
All of above	Heating	58’245	-29.4%	68’036	-28.8%	0.86	-0.8%
	Cooling	14’855	12.5%	9’413	12.8%	1.58	-0.2%

4.3. All interventions

Finally, the effect of all short-term and medium-term interventions has been evaluated. Results are in Table 6. With only short-term interventions the HVAC primary energy need is 25.3 kWh/m^{2}y. Adding medium-term interventions it passes to 17.0 kWh/m^{2}y. This is a quite strong absolute reduction but it has to be considered too low if compared to the entity of economic investments. For this reason only short-term interventions are considered to be highly effective with the present energy costs.

Table 6. HVAC useful and primary energy needs for all interventions.

	Useful energy [kWh]	Useful energy variations [%]	Primary energy [kWh]	Primary energy variations [kWh]	Mean seasonal efficiency	Mean seasonal efficiency variations
Heating	22’750	-72.4%	14’990	-84.3%	1.52	75.8%
Cooling	12’965	-1.8%	8’261	-1.0%	1.57	-0.7%

5. Conclusions

A simplified dynamic simulation on a historical building in Rome owned by ANCE has been realized. This leaded to important results.

First, it was verified that a simplified (single-zone) dynamic simulation is still highly reliable, with an error of about 5% compared to real measured data, but with a much shorter amount of work time.

Second it was showed that also in a historical building, where there are few degrees of freedom, with a good analysis it’s possible to find high saving potentials with low investments. In these cases it’s important to realize a measurement campaign to discover hidden control inefficiencies and energy wastes.

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